The Future of Millimetre and Submillimetre Cosmology

David H. Hughes

Instituto Nacional de Astrofisica, Optica y Electronica (INAOE),
Apartado Postal 51 y 216, 72000, Puebla, Pue., Mexico

Abstract

Using the submm array camera SCUBA on the 15-m JCMT it is now possible to conduct unbiased submm surveys and quantify the level of star-formation activity in the young Universe by observing the rest-frame FIR thermal emission from dust in high-redshift galaxies. However an accurate interpretation of these existing submm cosmological surveys is prevented by uncertainties in the redshifts of the submm-selected galaxies, the ambiguities in the identifications of their optical/IR and radio counterparts and the restricted range of flux density over which the submm source-counts are measured. This paper outlines the future observations required to overcome these deficiencies.

1 Introduction

Observational evidence suggests that much of the on-going star-formation in the young universe takes place in a heavily obscured ISM and therefore must be *hidden* from extragalactic optical and IR surveys. Hence the *transparent* view of the high-z universe provided by submm–mm wavelength observations ($\lambda \sim 200 - 3000\mu$m) which are insensitive to the obscuring effects of dust, and the strength of the negative k-correction which enhances the observed submm–mm fluxes of starburst galaxies by factors of 3–10 at $z > 1$ [7], offer obvious advantages.

The opportunity to conduct cosmological observations at submm–mm wavelengths has been realised in the last few years with the successful development and commissioning of sensitive bolometer arrays (*e.g.* SCUBA-I, SHARC-I, BoloCam-I, MPIfR 37-channel). These arrays, which will be upgraded within 1–2 years, operate on the largest submm and mm telescopes (15-m JCMT, 10-m CSO, 30-m IRAM).

2 Submillimetre Cosmological Surveys

By early 2001 the first series of extragalactic SCUBA (850 μm) surveys will be completed, covering areas of 0.002–0.12 deg^2 with respective 3σ depths in the range 1.5 mJy $<$ S$_\nu$ $<$ 8 mJy [9], [6], [1], [5], [8]. The evolution of the high-z starburst galaxy population can be determined from an accurate measure of the integral submm source-counts, the FIR luminosities, star formation rates (SFRs) and redshift distribution of the submm selected galaxies. The contribution of the submm sources to the total FIR - mm background places an additional constraint on the competing models. To ensure these submm data are fully exploited, the current SCUBA surveys have been restricted to fields that have been extensively studied at other wavelengths (X-ray, optical, IR and radio) and have yielded the following preliminary results:

- The faint submm source-counts at 850μm are reasonably well determined between 1–10 mJy and significantly exceed a no-evolution model, requiring roughly $(1+z)^3$ luminosity evolution out to $z \sim 2$, but with poor constraints at higher redshifts (fig. 1). The submm background measured by COBE requires that the SCUBA source-counts must converge at $S_{850\mu m} \leq 0.5$mJy. Approximately 30–50% of the submm background has been resolved into individual galaxies with flux densities $S_{850\mu m} > 2$ mJy.

- Submm sources generally appear to be associated with $z > 1$ galaxies, although it not clear whether they necessarily have optical, IR and radio counterparts. There is still much debate about the fraction of submm sources at $z \geq 2$, and the fraction of submm sources that contain an AGN.

- At high-redshift ($2 < z < 4$) the sub-mm surveys appear to find ~ 5 times the star formation rate observed in the optical surveys, although the effects of dust obscuration and incompleteness in the optical are still uncertain.

2.1 Limitations on an understanding of high-z galaxy evolution

Despite the success of the first SCUBA surveys, we can identify the deficiencies in the submm data which prevent a more accurate understanding of the star-formation history of high-z galaxies. This paper summarises these deficiencies and outlines the future observations which will alleviate the following problems.

2.1.1 *Poorly constrained evolutionary models*   To improve the constraints on the competing evolutionary models provided by the current submm source-counts, it is necessary to (1) extend the restricted wavelength range of the surveys, (2) increase the range of the flux densities over which accurate source-counts are measured and (3) increase the number of sources detected at a given flux level by surveying greater areas.

Ground-based surveys at mm wavelengths can take advantage of a more stable and transparent atmosphere which will provide increased available integration time (to gain deeper survey sensitivity or greater survey area) and increased flux calibration accuracy. Future surveys with more sensitive and larger format arrays (*e.g.* BoloCam) operating at 200μm $- 3$ mm on airborne and ground-based telescopes will allow signifcantly greater areas to be covered (hence more sources detected) and will increase the range of the flux densities over which sources are detected (fig 1.). The deepest surveys todate are still only sensitive to high-z galaxies with SFRs comparable to the most luminous local ULIRGs ($\geq 200 M_\odot \text{yr}^{-1}$). Furthermore conducting surveys with larger diameter telescopes (*e.g.* 50-m Gran Telescopio Milimetrico (LMT), 100-m GBT) will reduce the beam-size, hence decrease the depth of the confusion limit (allowing deeper surveys) and improve the positional accuracy of detected sources.

2.1.2 *Ambiguity in the optical counterparts & redshifts of submm galaxies*   The current SCUBA surveys (with $15''$ resolution at 850μm) are struggling to unambiguously identify the submm sources with their optical/IR/radio counterparts. Hence the redshift distribution and luminosities of the submm sources are still uncertain. This results directly from the submm positional errors of $\sim 2 - 3''$ that are typical for even the highest S/N submm detections, and from the lack of submm data measuring the redshifted FIR spectral peak at 200–450 μm.

The positions of the brightest SCUBA sources ($S_{850\mu m} > 8$ mJy) can be improved with mm-interferometric observations. However our IRAM Plateau de Bure follow-up of the brightest source in the Hubble Deep Field has demonstrated that even with $\leq 2''$ resolution and sub-arcsec positional errors, ambiguous optical identifications, and hence ambiguous redshifts remain [4].
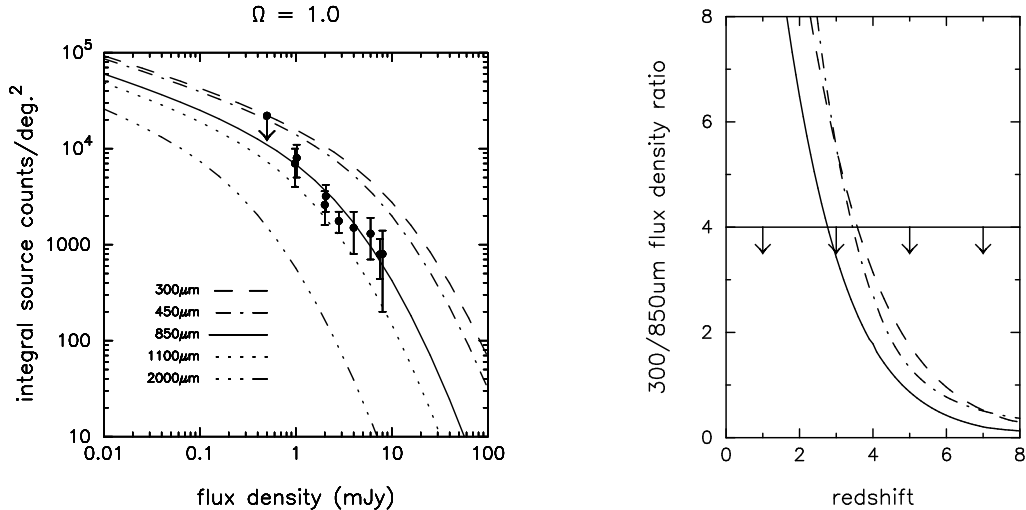
Figure 1: Predicted number-counts at submm and mm wavelengths. The data represent the measured 850μm source-counts from the SCUBA surveys described in §2. A representative evolutionary model at 850μm (pure luminosity evolution of the form $(1+z)^{3.0}$ out to z_u=2.3, with evolution then held constant between $2.3 \leq z_c < 6.0$) is extrapolated to derive the number counts at 300–2000μm. The data are consistent with a range of models (where $z_u \sim 2.0 - 3.0$ with an upper-bound of $z_c > 5.0$). More accurate submm and mm source-counts at brighter (>10 mJy) and fainter (<1 mJy) flux densities are required to fully constrain the competing models.

Figure 2: The $300/850\mu$m flux ratio, appropriate for the combination of BLAST and SCUBA surveys (§2.1.2), is a powerful discriminant of redshift. The example of a 4σ 850μm detection (10 mJy), from the medium-depth UK SCUBA survey, with no BLAST 300μm counterpart (< 40 mJy) is indicated by the horizontal line. This upper limit to the $300/850\mu$m ratio implies a redshift > 3 assuming the SED of the high-z source is similar to the range of low-z starburst and AGN SEDs represented by the solid (Arp220), dashed (M82) and dashed-dotted (Mkn231) curves.

It should be no surprise that submm selected galaxies, including those with mm-interferometric detections, do not always have optical counterparts since high-z galaxies observed in the earliest stages of formation may be heavily obscured by dust. Indeed this is the most compelling reason for conducting the submm surveys in the first instance and therfore searches for the counterparts may be more successful at near-infrared wavelengths. This was recently demonstrated by Smail *et al.* [10] who took deep near-IR (2μm) images of two lensed clusters previously observed by SCUBA [9]. The original counterparts were identified as bright low-redshift ($z \sim 0.4$) galaxies 5–10 arcsecs distant from the submm sources. However the new IR images revealed two high-z ($z > 2$) IR galaxies, with no optical counterparts, within 2–3 arcsecs of the SCUBA sources. The obvious consequence of these misidentifications is an inaccurate determination of the star-formation history of high-z starburst galaxies.

The uncertainty in the redshift distribution of submm-selected galaxies can be significantly reduced by measuring the mid-IR to radio SEDs of the individual sources. The power of using mid-IR to radio flux ratios (*e.g.* $15/850\mu$m, $450/850\mu$m, 850μm/1.4 GHz) as a crude measure of redshift was demonstrated by Hughes *et al.* [6] during the SCUBA survey of the Hubble Deep Field and has since been described elsewhere [3], [2]. Given sufficient sensitivity, the mid-IR–submm–radio colours of a submm source can discriminate between optical/IR counterparts which are equally probable on positional grounds alone, but which have significantly different redshifts, $\delta z \geq 2$, (fig. 2). This important technique, and the necessity for sensitive short submm data (200–500μm) measuring the rest-frame FIR SEDs of the individual high-z submm galaxies, without which it remains impossible to constrain their bolometric luminosities and SFRs, provide the major scientific justifications behind *BLAST*, a possible future long-duration Balloon-borne Large Aperture Submm Telescope (P.I. M.Devlin, University of Pennsylvania).

survey area (sq. degrees)	1σ depth	no. of pixels	no. of detected galaxies $> 5\sigma$	$> 10\sigma$	no. of $> 5\sigma$ galaxies $z > 1$	$z > 3$
6 hour 300 μm test-flight survey: D=2.1 m, $\theta = 41''$, NEFD=150 mJy s$^{1/2}$						
0.24	7 mJy	2352	120	34	110	18
0.55	10 mJy	4800	150	40	135	20
1.1	15 mJy	10800	135	30	125	16
50 hour 300 μm long-duration flight survey: D=2.7 m, $\theta = 32''$, NEFD=90 mJy s$^{1/2}$						
3.3	7 mJy	32884	1670	480	1530	250
6.8	10 mJy	67111	1870	500	1680	250
15.4	15 mJy	151000	1890	420	1740	220

Table 1: Number and z-distribution of galaxies detected in alternative BLAST surveys.

Alternative *BLAST* 300μm surveys based on the model shown in fig 1 are described in Table 1. Assuming a 3σ 300μm confusion limit of $\sim 20 - 30$ mJy, a single 6 hour *BLAST* test-flight survey can follow-up the widest of the current SCUBA surveys, detecting all $> 4\sigma$ SCUBA sources (~ 100 sources with $S_{850\mu m} > 10$ mJy) in a 0.24 sq. deg. survey at all redshifts < 3. Non-detections at 300μm imply $z > 3$. Increasing the primary aperture of *BLAST* to 2.7-m and conducting a 50-hour survey during a long-duration balloon flight significantly increases the survey area and number of sources detected to > 1500, a comparable number to that detected by BoloCam in a future 50-hour 0.45 sq. degree 1100μm survey with the GTM/LMT.

An accurate determination of the redshift distribution of submm selected galaxies will ultimately be achieved through the measurement of mm-wavelength ^{12}CO spectral-line redshifts, without recourse to having first identified the correct optical or IR counterparts. This "CO *redshift machine*" requires a large instantaneous bandwidth ($\Delta\nu \sim 30 - 40$ GHz) to take advantage of the reduced separation of adjacent mm-wavelength ^{12}CO transitions in the high-z universe, $\delta\nu_{J,J-1} \sim 115/(1 + z)$ GHz. Hence at redshifts > 2 any adjacent pair of ^{12}CO lines are separated by < 40 GHz, the frequency separation defining the precise redshift of the galaxy. The combination of data from BLAST, JCMT, CSO and the GTM/LMT will efficiently pre-select from submm surveys, using their FIR–mm colours, those galaxies with sufficiently high (but still unknown) redshifts that are suitable targets to follow-up with a "CO *redshift machine*".

References

[1] Barger, A. *et al.* 1998, *Nature* **394**, 248

[2] Blain, A., 1999, astro-ph/9906438, *MNRAS* in press

[3] Carilli, C., Yun, M.S., 1999, astro-ph/9812251, *Astrophys. J.* in press

[4] Downes, D. *et al.* 1999, *Astr. Astrophys.* **347**, 809

[5] Eales, S.A. *et al.* 1999, *Astrophys. J.* **515**, 518

[6] Hughes, D.H. *et al.* 1998, *Nature* **394**, 241

[7] Hughes, D.H., Dunlop, J.S. 1999, in *Highly Redshifted Radio Lines*, A.S.P. Conf Ser. 156, p.99, astro-ph/9802260

[8] Lilly, S. *et al.* 1999, *Astrophys. J.* **518**, 441

[9] Smail, I. *et al.* 1997, *MNRAS* **490**, L5

[10] Smail, I. *et al.* 1999, astro-ph/9905246, *MNRAS* in press